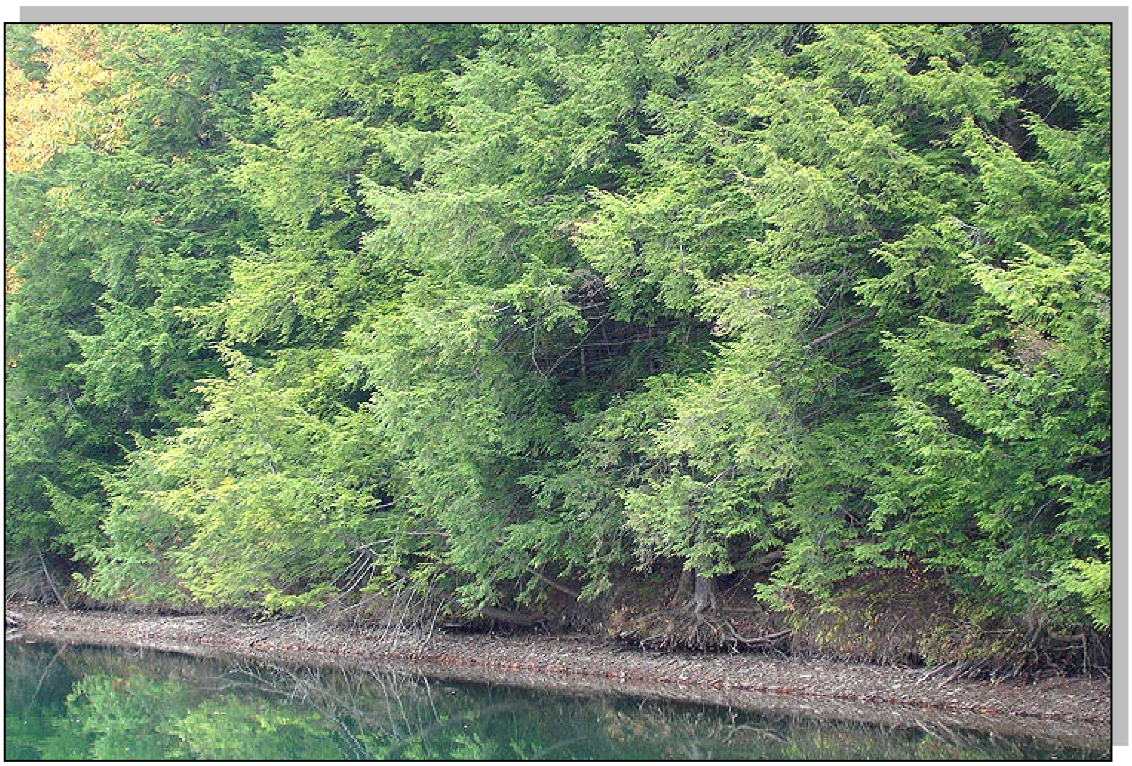
Biological Evaluation
of
Hemlock Woolly Adelgid
at
Raystown Lake,
Hesston, Pennsylvania



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February 2006

ABSTRACT

In the fall of 2005 the USDA Forest Service with assistance from Raystown Lake personnel, conducted surveys to evaluate hemlock woolly adelgid (HWA), *Adelges tsugae* population densities at Raystown Lake, and to assess the need for treatment. Current populations are sufficient to impact tree health in some of the areas surveyed and the use of imidacloprid is recommended in stands where high-valued infested hemlock trees occur.

INTRODUCTION

HEMLOCK WOOLLY ADELGID

Adelgids are small, soft-bodied insects that feed exclusively on conifers. The family is divided into two genera: *Adelges* and *Pineus*. There are six species of *Adelges* that occur in North America, of which only one is native (Montgomery 1999), the Cooley spruce gall aphid (*Adelges cooleyi*). This adelgid occurs coast to coast in northern North America. Its primary hosts are recorded as white (*Picea glauca*), blue (*Picea pungens*), Sitka (*Picea sitchensis*), and Engelmann (*Picea engelmannii*) spruce (Baker 1972). It has an alternate host, Douglas fir (*Pseudotsuga menziesii*). There are 10 species of *Pineus* that occur in North America, of which seven are native. Four of these the pine bark adelgid (*Pineus strobi*); the pine leaf adelgid (*P. pinifoliae)*; the red spruce adelgid (*P. floccus*); and the spruce gall adelgid (*P. similes*) seem to be indigenous to eastern North America (Drooz 1989, Montgomery 1999). These species attack eastern white pine (*Pinus strobus*), red spruce (*Picea rubens*), and black spruce (*Picea mariana*) but seldom cause extensive damage (Drooz 1989, Montgomery 1999). Little is known about the population dynamics, ecological role, or the predator complex associated with these native adelgids.

Native to Asia, the hemlock woolly adelgid (*Adelges tsugae)* is a pest of eastern hemlock (*Tsuga canadensis*) and Carolina hemlock (*T. caroliana*) (Onken et al. 1999), both of which are considered highly susceptible to the adelgid, with no documented resistance (Bentz et al. 2002). The latter tree species is found only in the southern region of the Appalachian Mountains (Onken et al. 1999). The HWA is currently established in 16 Eastern States from Georgia to Maine, and tree decline and mortality have increased at an accelerated rate since the late 1980s. For example, in the Shenandoah National Park (SNP), hemlock crown health has declined since the early 1990s. In 1990, greater than 77 percent of the hemlocks sampled were in a "healthy" condition; by 1999, less than 10 percent were in a "healthy" condition (Akerson and Hunt 1998). In another study at SNP, tree mortality significantly increased from an initial 8 percent in 1990 to nearly 50 percent in 2000 (Bair 2002). In New Jersey twelve years after initial HWA infestations, tree mortality reached more than 90% in some hemlock stands (Mayer et al 2002).

The hemlock woolly adelgid is parthenogenetic (an all-female population with asexual reproduction) that has six stages of development: the egg, four nymphal instars, and the adult, and two generations a year on hemlock. The winter generation, the sistens, develops from early summer to midspring of the following year (June-March). The spring generation, the progrediens, develops from spring to early summer (March-June). The generations overlap in mid to late spring.

The hemlock woolly adelgid is unusual in that it enters a period of dormancy during the hot summer months. Prior to dormancy, the nymphs produce a tiny halo of wool-like wax filaments surrounding their bodies. The adelgids begin to feed once cooler temperatures prevail, usually in October and

continue throughout the winter months. As it matures this woolly covering increases in size and becomes more conspicuous. This woolly sac (ovisac) helps protect the insect and its eggs from natural enemies and prevents them from drying out. These ovisacs can be readily observed from late fall to early summer on the underside of the outermost branch tips of hemlock trees.

The ovisacs of the winter generation contain up to 300 eggs, while the spring generation ovisacs contain between 20 and 75 eggs. The hemlock woolly adelgid also has a winged form that is produced by the spring generation. This form must complete part of its life cycle on spruce. The apparent lack of a suitable spruce host for this form in eastern North America results in a substantial loss of adelgids each year (McClure 1992b). Although natural mortality in HWA populations is commonly between 30 to 60 percent (McClure 1989, 1996), the reproduction potential of this insect remains high. Other mortality is generally attributed to two likely causes: 1) an extended period of cold temperatures or rapid temperature changes that coincides with a susceptible period of development for the adelgid, and/or 2) a sufficient loss in the nutritional quality and quantity of the food source, which is associated with the decline in health and vigor of the host tree (McClure 1996, Onken et al. 1999).

Adelgid feeding can kill a mature tree in about 5 to 7 years (McClure et al. 2001). This tiny insect (~ 1 mm) feeds on all life stages of hemlock, from seedling to mature, old growth tree. The first instar nymphs, called crawlers, search for suitable sites at the base of the hemlock needles, and insert their feeding stylets into the young hemlock twigs and are committed to that feeding site throughout the remainder of its development. The stylet bundle is more than three times the length of the insect and penetrates deep within the plant tissues. HWA does not deplete nutrients directly by feeding on the sap, but rather by depleting the food reserves from the tree's storage cells (McClure et al. 2001).

Dispersal and movement of HWA during its egg and mobile first instar stages is associated with wind, birds, deer, and other forest dwelling mammals. Humans also move the adelgid during logging and recreational activities and movement of infested nursery stock (McClure 1995). Natural enemies capable of maintaining low-level HWA populations are nonexistent in eastern North America (Van Driesche et al. 1996, Wallace and Hain 1998).

HWA was first reported in the western U.S. in the 1920s (Annand 1924, McClure 2001). HWA populations on western tree species, including western hemlock (*Tsuga heterophylla*) and mountain hemlock (*T. mertensiana*), appear to be innocuous; these tree species are believed to be resistant because little damage has been reported (McClure 2001). Unfortunately, both these trees are of limited value for hybridization and planting due to their poor adaptation to the east coast environment (Bentz et al. 2002). In the East, HWA was first reported in 1951 near Richmond, Virginia. It was considered to be more of an urban landscape pest and was controlled using a variety of insecticides applied with ground spraying equipment. Observations of the adelgid were periodically reported in several Mid-Atlantic States in the 1960s and 1970s but it was not until the 1980s that HWA populations began to surge and spread northward to New England at an alarming rate. By the late 1980s to early 1990s, infestations of HWA were reported to be causing extensive hemlock decline and tree mortality in hemlock forests throughout the East (McClure 2001).

HEMLOCK IMPORTANCE

Eastern hemlock is an extremely shade tolerant tree species, capable of surviving for as long as 350 years underneath a shaded forest canopy (Quimby, 1996). It is a slow-growing long-lived tree. It may take 250-300 years to reach maturity and may live for 800 years or more (Godman and Lancaster 1990).

Eastern hemlock forests create distinctive microclimates and provide important habitat for a variety of wildlife, such as birds, fish, invertebrates, amphibians, reptiles and mammals. In the Northeast, 96 bird and 47 mammal species are associated with hemlock forests at some point during their life (Yamasaki et al. 2000).

Hemlocks located along the shoreline of the lake are of aesthetic value and provide valuable wildlife habitat along the small streams and spring channels. Because of the limited hemlock habitat at Raystown Lake, resource managers have expressed a high priority to protect these trees.

HWA HISTORY AND OTHER STRESSORS AFFECTING HEMLOCK HEALTH CONDITIONS AT RAYSTOWN LAKE

HWA was first discovered at Raystown Lake in 1999 at the northern end of the lake. In 2002, a survey was conducted to determine the extent and magnitude of HWA infestations. Over 160 acres of hemlocks were surveyed and about 144 acres were determined to be infested with HWA.

The impacts of HWA and the droughts of recent years have stressed hemlock resources at Raystown Lake. So far, over 100 mature hemlock trees have succumbed.

A summary of hemlock woolly adelgid treatments at Raystown Lake is presented in Table 1.

In the fall of 2003, over 200 trees in stand 1 received trunk injections of a systemic insecticide imidacloprid (Pointer®), at 5 percent active ingredient to control HWA. In the spring of 2004, approximately 1,000 additional trees were treated in stands 1-4, 7, and 10 using the same treatment.

In the spring of 2004, 5,000 *Sasajiscymnus tsugae* (*S.t*) beetles were released in 2 locations (2,500/location) in Stand 6.

In the fall of 2004, chemical treatments for the control of HWA were applied using imidacloprid via. trunk injections (Pointer®) and soil injections (Merit®). Trunk injections were conducted on 1,119 trees in 15 stands (stands 2-5, 10, 12-16, 19, 20, 25, and 27) and 43 trees received soil injections in stand 24.

Hemlocks exhibiting declining health conditions were also treated with an experimental micronutrient supplement at Raystown Lake. A total of 851 trees were treated with a soil injected micronutrient supplement in stands 1, 3, 4, 10, 12, 14, 15, 16, 17, 19, 20, 23, 25, and 27. A total of 282 hemlocks in stands 1, 2, 5, 10, 13, and 27 received a soil injected micronutrient supplement in combination with a Merit® treatment and a total of 25 acres of hemlocks trees in stand 1, 2 and 10 were aerially treated with a micronutrient supplement only.

In the fall of 2005, chemical treatments were applied via trunk injections using imidacloprid (Pointer®) on 1, 305 trees in 14 stands (stands 2, 3c, 4, 5, 10, 12, 13a, 14, 15, 16, 19, 20, 25, and 27a-b) and stands 18a and 25 were treated with fertilizer.

METHODS

Live hemlock trees (> 6" DBH) were randomly selected for inspection within the survey areas based on accessibility into the selected stands. An assessment of tree vigor, branch tip dieback, new shoot growth, DBH (estimated tree diameter at breast height to nearest inch), and HWA population densities was conducted of each tree.

A GPS (global positioning system) unit was used to collect coordinates (decimal degrees, WGS84) to track the area surveyed within the stands. A GPS point was taken to represent the general area of each plot. The number of trees per plot varied based on the availability of hemlock trees with branches that could be reached.

Up to four branch samples, each 30 centimeters in length, were selected from the lower crown from different sides of the tree. HWA infestation density levels were designated as heavy, moderate, light or none based on the percentage of tips with adelgid present and categorized as follows:

Heavy (H) = (>50% infested)
Moderate (M) = (50% to 25% infested)
Light (L) = (<25% infested)
None (N) = (0% infested)

Vigor ratings represent the general health of the tree based on:

Healthy (H) = tree appears to be in reasonably good health: less than 10% branch or twig mortality, discoloration, or dwarfed leaves present
Light Decline (LD) = branch mortality, twig dieback, foliage discoloration, or dwarfed leaves present on 10-25% of the crown
Moderate Decline (MD) = branch morality, twig dieback, foliage discoloration or dwarfed leaves on 26-50% of crown
Severe Decline (SD) = more than 50% of the crown with branch mortality, dieback, discoloration or leaf dwarfing, but foliage still present indicating that the tree is alive

Relative abundance of new growth and shoot tip dieback was estimated by assessment of each shoot tip within 30 centimeters of branch length, divided by the total number of tips on each branch sample.

RESULTS

Stands 1-6, 8-15, 17-20, 22-25, and 30 were surveyed and are represented in Figures 1a-f, and the survey data is presented in Appendix A. The results of the tree level data and of the stand level data are summarized in Table 2 and Table 3, respectively. Hemlock woolly adelgid infestations and tree health ratings are variable from stand to stand and even tree to tree throughout the survey area.

In stands 20 and 24b, trees are generally healthy and HWA infestations were undetectable.

In stands 5, 9, 18b, and 23, trees are generally healthy and HWA population densities are generally light.

In stand 25, trees are in light decline and populations of HWA are generally moderate.

In stands 15, 18c, and 22, trees are in light decline and HWA population densities are high.

In stand 1, trees are generally in moderate decline. Populations of HWA are generally light.

In stands 13a-b, 14, and 17, trees are generally healthy to showing signs of light decline and HWA populations are moderate.

In stands 3a, 8, and 24a, trees are generally healthy to showing signs of moderate decline and HWA population densities are light.

In stands 3, 4, 6, 11, 18a, and 30, trees are healthy to showing signs of moderate decline and HWA population densities are high.

In stands 3b, 12b-c, and 18a, trees are in moderate decline and HWA population densities are high.

In stand 10, trees are generally in moderate to severe decline and HWA population densities are light.

In stands 2, 12a, and 19, trees are generally in moderate to severe decline and HWA population densities are moderate.

No individual tree data was collected for stands 26, 28, and 29. Trees in this area were very scattered and generally in severe decline.

No plots were established in stand 31, since the trees are in good health and no HWA populations were observed.

DISCUSSION

HWA population densities and tree health conditions are highly variable between and within the 30 hemlock stands surveyed at Raystown Lake. For example, many stands have trees that are in relatively good health but have HWA infestations ranging from none to high. Stands 2, 10, 12a, and 19 have tree health ranging from moderate to severe decline with HWA population densities ranging from light to moderate. Likewise, tree health in stands 3b, 4, 6, 12c, 15, 18a, 18c, 22, and 30 ranges from healthy to moderate and HWA population densities are generally high. It is an easy matter to recommend treatments wherever HWA infestations occur, however the logistical complexity of the available treatments, the scope of the hemlock resource within the Project and limited budgets, make these decisions difficult in the absence of a further understanding of resource values and priorities.

As such, it is important that resource managers develop a means to prioritize the hemlock resources at the Raystown Lake Project by developing a HWA Management Plan. This plan would evaluate each stand and weigh the values associated with its recreation, aesthetics, wildlife habitat (particularly T&E species), timber and erosion control and other attributes deemed important. The plan should also consider treatment strategies which might include decisions to treat only portions of stands (e.g. within 100 feet of the waters edge for aesthetic purposes, or to focus on protecting a selected number of larger trees dispersed throughout the stand to maximize better seed dispersal). Ultimately, the plan provides the guidance for future management and control of HWA rather than a random haphazard approach.

The remainder of this discussion will focus on available treatment options and provides further considerations for development of a management plan.

Management Options

Chemical management options for preserving hemlock stands are limited by the biology and feeding behavior of HWA, pest population densities, site conditions (i.e. proximity to streams), accessibility and limited application technology currently available. Insecticide treatments although effective, are conducted on an individual tree basis which can be both labor intensive and costly. Thus treatment strategies are typically focused in high value sites such as recreational or scenic areas or where hemlock stands are known to play an important ecological role. Classical biological controls such as predators and pathogens are being pursued by the USDA Forest Service but will likely take years to become effectively established. As such, preservation of hemlocks in the short term will require intensive monitoring and periodic chemical treatments when infestations are discovered.

Foliar chemical treatments. Aerial spray using horticultural oil or insecticidal soap is not an option because aerial sprays could not provide the needed "saturation" necessary to ensure that the insecticide adequately covers the insect. Aerial spraying with more toxic insecticides (e.g. malathion or diazinon) would have very significant, unacceptable impacts on a wide range of non-target insects and other animals and limited control benefits (Evans 2000). Application of insecticides using ground spraying equipment is generally limited to areas accessible to hydraulic spray equipment and areas where over spray or run off would not contaminate streams, lakes or ponds. Backpack sprayers could be effectively used for foliar treatment of infested seedlings and saplings in more remote areas.

Systemic Insecticides. Several systemic insecticides are labeled for adelgids and can be injected (e.g. imidacloprid, bidrin or Metasystox-R®) or implanted (e.g. acephate) into hemlock trees, and another (Merit®) can be applied as a soil drench or injected into to the soil around hemlock trees. These insecticides are absorbed and trans-located by the vascular system of the tree to feeding adelgids and will effectively suppress HWA populations (Doccola et al. 2003, Webb et al. 2003, Evans 2000, Steward and Horner 1994, McClure 1992a). Soil injection in sandy or saturated soils should be avoided as leaching of the insecticide into the soil profile and groundwater (McAvoy et al. 2002) is a possibility. Soil injections immediately adjacent to creeks or other open waters should also be avoided. Imidacloprid formulated as a trunk injection is available under the trade names Pointer®, IMA-jet® and Imicide® and are labeled for tree injection for the control of adelgids. However, only IMA-jet® and Imicide® are labeled for applications in the forest environment. Both stem and soil treatments of imidacloprid have become the preferred treatment for HWA in high value hemlock stands by state and federal resource managers. A further discussion of this product follows.

Imidacloprid is a relatively new insecticide in the family of chemicals called neonicotinoids (Felsot 2001) in the chloronicotinyl subgroup (USDA Animal and Plant Health Inspection Service 2002). It has a mode of action similar to that of the botanical product nicotine, functioning as a fast-acting insect neurotoxicant (Schroeder and Flattum 1984) that binds to the nicotinergic receptor sites in the postsynaptic membrane of the insect nerve (USDA Animal and Plant Health Inspection Service 2002), mimicking the action of acetylcholine, and thereby heightening, then blocking, the firing of the postsynaptic receptors with increasing doses (Schroeder and Flattum 1984, Felsot 2001). Because imidacloprid is slowly degraded in the insect, it causes substantial disorder within the nervous system, leading in most cases to death (Mullins 1993, Smith and Krischik 1999).

Imidacloprid is considered to have low to moderate mammalian toxicity (Mullins 1993), largely because it does not bind nerve receptors in mammals sufficiently to trigger nervous activity (Felsot 2001). The selective toxicity of imidacloprid is perhaps best illustrated by its use in flea treatments approved for cats and dogs. Advantage® is applied directly to the animal's skin; this preparation carries very little, if any, risk to the animal or to the people, including children, who may handle the animal (USDA Animal and Plant Health Inspection Service 2002). Chronic (repeated dose) toxicity studies have demonstrated that imidacloprid is not carcinogenic and is not mutagenic and demonstrates no primary reproductive toxicity (Mullins 1993). In studies of metabolic fate in rats, imidacloprid was rapidly absorbed and eliminated in the excreta (90 percent of the dose within 24 hours) with little bioaccumulation (0.5 percent of the dose after 48 hours) and no biologically significant differences occurring between sexes, dose level, and route of administration (USDA Animal and Plant Health Inspection Service 2002). Imidacloprid is an insecticide exhibiting both systemic and contact activity. The spectrum of activity primarily includes sucking insects (aphids, whiteflies, leaf and plant hoppers, thrips, plant bugs, and scales), many Coleopteran species, and selected species of Diptera and Lepidoptera. Activity has also been demonstrated for ants (Hymenoptera); termites (Isoptera); and cockroaches, grasshoppers, and crickets (Orthoptera). No activity has been demonstrated against nematodes or spider mites (Mullins 1993). In spider mites, imidacloprid has been demonstrated to cause an egg-laying enhancement (James and Price 2002). Since spider mites can be a problem in ornamental hemlocks, open-grown imidacloprid-treated trees should be carefully monitored for increases in mite populations.

Little is known about the biotransformation and bioactivity of the metabolites of imidacloprid in hemlock. What is known is that trunk-injected imidacloprid generally requires a week or longer to provide adelgid control, with protection lasting for up to 2 years (Tater et al. 1998, Silcox 2002). The soil injection or soil drench methods of imidacloprid treatments take several months for translocation to occur but typically has provided better consistency in treatment efficacy when compared to stem injections. Stem injections should not be used on severely stressed trees.

***Biological control*:** There are no known parasites of adelgids. The first predator beetle to be imported and released for biological control is a tiny, black lady beetle, *Sasajiscymnus tsugae* (*S.t*), from Japan. Since 1995, over a million *S.t* beetles have been released in over 200 sites in 15 eastern states from Georgia to Maine. Several species of *Scymnus* lady beetles from China and a derodontid beetle *Laricobius nigrinus* from the Pacific Northwest are also approved for release. Establishment of the latter predators began in 2004. Where these natural enemies are released is the responsibility of state forest health specialists from each state and the USFS. All of the releases are in infested hemlock stands found primarily along the leading edge of the generally infested area, where hemlocks are still healthy and HWA densities have not yet overwhelmed the trees. The release and establishment of HWA natural enemies is not likely to provide short term control of HWA. It is rather a long term approach which will likely require a complex of natural enemies to maintain HWA below damaging levels and years before these predators can self perpetuate sufficiently. Only then can we measure any level of success.

Release of predator beetles should not take place in close proximity of hemlock trees that have received chemical treatments because of the effect of the chemical insecticide may have on beetles should they feed on adelgids that ingest the insecticide. Preferred release sites are newly infested sites where trees and adelgids are still healthy. Predator beetles are laboratory reared and the number of predators available in any given year is variable depending in part, on the success of the rearing facilities to locate good quality host material for a food source. Artificial diets are not yet available.

RECOMMENDATIONS

The use of imidacloprid based insecticides is recommended for use on high-valued infested hemlock trees only. Repeated treatment of entire stands is logistically impractical and cost prohibitive. High-value hemlocks in stands 1-6, 8-15, 17-19, 22-24a, 25, and 30 should be considered. Where possible, soil injections are preferred over stem injections as treatment efficacy has been shown to be more consistent. Merit® applied at 1 ounce per 30 cumulative inches of trunk diameter (dbh) is recommended for the soil injections, and treatment timing should be in the spring or fall. The insecticide recommended for the stem injections is IMA-jet® at 5% active ingredient with the number of application sites determined by dbh. Criteria for number of application sites is as follows: 4 application sites for 6-16 inches dbh, then add one additional application site for each additional 4 inches of dbh. Hemlocks tend to have faster uptake of the stem injected insecticide in the mornings during the spring and fall months with cooler temperatures and higher humidity.

With treatment options comes the potential for non-target effects; land managers must balance the risk of these effects with the potential benefits that come with the control of the HWA. As a best management practice, the USFS has previously recommended that hemlocks within 50 feet of open water be treated with a stem injection rather than a soil treatment. Research at the CT Agricultural Research Station has recently demonstrated that imidacloprid binds tightly with organic soils such that movement more than a few centimeters is unlikely when the chemical is placed in the organic layer of the soil. Imidacloprid will leech through mineral soils quite readily so more important than the 50 foot buffer is that applicators use good judgment as to placement of the injector tip in organic soils which in most cases, is less than 3 inches deep. This depth also coincides with the shallow feeder roots of eastern hemlock. With this new research information, soil treatments closer to open water may be acceptable when treatment decisions are based on the soil conditions surrounding each tree to be treated within the 50 foot buffer. In circumstances where rocky porous soils exist or the organic layer in not sufficiently deep to handle the injector tip placement, trees should be treated using a stem injection system. Ground spraying using horticultural oil to protect hemlock seedlings and saplings by means of a backpack sprayer should be considered in areas where protecting younger hemlocks is desirable and where over spray or run off would not contaminate streams, lakes or ponds. One or two applications of a 2% solution of horticultural oil applied in early summer or early fall is recommended as adelgids have not yet developed the wool covering that can impede penetration of the insecticide.

Resource managers should annually monitor tree health conditions, adelgid population densities and treatment efficacy. Effective management of HWA requires a vigilant monitoring and treatment program until sufficient biological control agents are established. It is not logistically or economically feasible to chemically treat all trees in numerous or large hemlock stands. Resource managers are encouraged to develop a Raystown Lake HWA Management Plan that addresses specific hemlock values and provide a basis from which to prioritize treatment areas and management strategies.

REFERENCES

Akerson, J. and G. Hunt. 1998. HWA status at the Shenandoah National Park. USDA, Forest Service. Hemlock Woolly Adelgid Newsletter # 3: 10-11.

Annand, P.N. 1924. A new species of *Adelges* (Hemiptera: Phylloxeridae). Pan-Pac. Entomol. 1: 79-82.

Avery, M.L., D.G. Decker, D.L. Fisher and T. R. Stafford. 1993. Response of captive blackbirds to the new insecticidal seed treatment. J. Wildl. Manage. 57(3): 652-656.

Bair, M.W. 2002. Eastern Hemlock (*Tsuga Canadensis*) Mortality in Shenandoah National Park. In: Onken, B., R. Reardon, and J. Lashomb (Eds.), Proceedings, Symposium on the hemlock woolly adelgid In Eastern North America, February 5-7, 2002, East Brunswick, NJ. N.J. Agricultural Experiment Station Rutgers. 62-66p.

Baker, W.L. 1972. Eastern forest insects. USDA, Forest Service. Miscellaneous Publication No. 1175. 642 p.

Battles, J.J., N. Cleavitt, T.J. Fahey, and R.A.Evans. 2000. Vegetation composition and structure in two hemlock stands threatened by hemlock woolly adelgid. In: Proceedings of a Symposium on Sustainable Management of Hemlock Ecosystems in Eastern North America, edited by K.A. McManus, K.S. Shields, and D.R. Souto. Pp.55-61.

Bentz, S.E., L.G.H. Riedel, M.R. Pooler, and A. Townsend. 2002. Hybridization and self-compatibility in controlled pollinations of eastern north American and asian hemlock (*Tsuga*) species. Journal of Arboriculture 28(4): 200-205.

Butin, E., M. Montgomery, N. Havill, and J. Elkinton. 2002. Pre-release host range assessment for classical biological controls: Experience with predators for the hemlock woolly adelgid. In: Onken, B., R. Reardon, and J. Lashomb (Eds.), Proceedings, Symposium on the hemlock woolly adelgid In Eastern North America, February 5-7, 2002, East Brunswick, NJ. N.J. Agricultural Experiment Station Rutgers. 205-213 p.

Chaney, W.R. 1986. Anatomy and physiology related to chemical movement in trees. Journal of Arboriculture 12(4): 85-91.

Cheah, C.C. 1998. Establishing *Pseudoscymnus tsugae* (Coleoptera: Coccinellidae) as a biological control agent for hemlock woolly adelgid. Environmental Assessment prepared by the Connecticut Agricultural Experiment Station. Unpub. Report. 6 p.

Cheah, C. A. S.-J. and M.S. McClure. 2000. Seasonal synchrony of life cycles between the exotic predator, Pseudoscymnus tsugae (Coleoptera: Coccinellidae) and its prey, the hemlock woolly adelgid Adelges tsugae (Homoptera: Adelgidae). Agric. and For. Entom. 2:241-251.

Doccola, J.J. P.M. Wild, I. Ramasamy, P. Castillo, and C. Taylor. 2003. Efficacy of arborjet viper microinjections in the management of hemlock woolly adelgid. Journal of Arboriculture. 29(6): 327-330.

Drooz, A.T. 1989. Insects of eastern forests. USDA, Forest Service. Micellaneous Publication No. 1426. 608 p.

Evans, R.A. 2000. Draft Environmental Assessment: for the Release and Establishment of *Pseudoscymnus tsugae* (Coleoptera: Coccinellidae) as a Biological Control Agent for Hemlock Woolly Adelgid (*Adelges tsugae*) at the Delaware Water Gap National Recreation Area. USDI, National Park Service, Northeastern Region. 23 p.

Evans, R.A. 2003. Hemlock Ecosystems and Hemlock Woolly Adelgid at Delaware Water Gap National Recreation Area. USDI, National Park Service, Northeastern Region. 20p.

Felsot, A. 2001. Admiring Risk Reduction: Does Imidacloprid have what it takes? Agrichemical and Environmental News 186: 2-13.

Godman, R.M. and K. Lancaster. 1990. *Tsuga canadensis* (l.) Carr., eastern hemlock. In: R.M. Burns and B.H. Honkala, eds. Silvics of North America, vol.1, conifers. USDA Forest Service, Agriculture Handbook No. 654. pp. 604-612.

Helms, J.A., ed. 1998. The dictionary of forestry. The Society of American Foresters. Bethesda, MD.

Hennessey, R.D. and M.S. McClure. 1995. Field release of a non-indigenous lady beetle, *Pseudoscymnus* sp. (Coleoptera: Coccinellidae), for biological control of hemlock woolly adelgid, *Adelges tsugae* (Homoptera: Adelgidae). Environmental Assessment prepared by USDA, Animal and Plant Health Inspection Service, Riverdale, MD. Unpub. Report. 6 p.

Hepting, G.H. 1971. Diseases of forest and shade trees of the United States. USDA Forest Service, Agricultural Handbook 386. 488-491.

James, D.G. and T.S. Price. 2002. Imidacloprid boosts TSSM egg production. Agrichemical and Environmental News 189: 1-11.

Mayer, M., R. Chianese, T. Scudder, J. White, K. Vongpaseuth, and R. Ward. 2002. Thirteen Years of Monitoring the Hemlock Woolly Adelgid In New jersey Forests. In: Onken, B., R. Reardon, and J. Lashomb (Eds.), Proceedings, Symposium on the hemlock woolly adelgid In Eastern North America, February 5-7, 2002, East Brunswick, NJ. N.J. Agricultural Experiment Station Rutgers. 50-60 p.

McAvoy, T., W. Mays, S.M. Salom and L.T. Kok. 2002. Preliminary report of the impact of Merit (Imidacloprid) on hemlock woolly adelgid (Adelges tsugae) and non-target species. Department of Entomology, Virginia Polytech Institute and State University, Blacksburg, VA. Unpub. Report. 14 p.

McClure, M.S. 1989. Evidence of a polymorphic life cycle in the hemlock woolly adelgid, *Adelges tsugae* (Homoptera: Adelgidae). Ann. Entom. Soc. Am. 82:50-54.

McClure, M.S. 1992a. Effects of implanted and injected pesticide and fertilizers on the survival of Adelges tsugae (Homoptera: Adelgidae) and on the growth of Tsuga canadensis. Journal Econ. Entomol. 85(2) 468-472.

McClure, M.S. 1992b. Hemlock woolly adelgid. American Nurseryman 175(6): 82-89.

McClure, M.S. 1995. Managing hemlock woolly adelgid in ornamental landscapes. Bulletin 925. Connecticut Agricultural Experiment Station. 7 p.

McClure, M.S. 1996. Biology of *Adelges tsugae* and its potential for spread in the Northeastern United States. In: Salom, S.M., T.C. Tigner, and R.C. Reardon, (Eds.), Proceedings, First hemlock woolly adelgid review, 12 October, 1995, Charlottesville, VA. USDA, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV, FHTET-96-10: 16-25.

McClure, M.S. 2001. Biological control of hemlock woolly adelgid in the Eastern United States. USDA, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV, FHTET-2000-08. 10 p.

McClure, M.S. and C.A.S-J. Cheah. 1998. Released Japanese ladybugs are multiplying and killing hemlock woolly adelgids. Frontiers of Plant Science. 50(2): 6-8 p.

McClure, M.S. and C.A.S-J. Cheah. 2002. Establishing Pseudoscymnus tsugae Sasaji and McClure (Coleoptera:Coccinellidae) for the biological control of the hemlock woolly adelgid, Adelges tsugae, Annand (Homoptera:Adelgidae), in the Eastern United States. In: Onken, B., R. Reardon, and J. Lashomb (Eds.), Proceedings, Symposium on the hemlock woolly adelgid In Eastern North America, February 5-7, 2002, East Brunswick, NJ. N.J. Agricultural Experiment Station Rutgers. 351-352 p.

McClure, M.S., S.M. Salom, and K.S. Shields. 2001. Hemlock woolly adelgid. USDA, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV, FHTET-2001-03. 14 p.

Millington, W. 1989. Hemlock woolly adelgid infestations discovered. Fall Newsletter of the Research and Resource Planning Division of Delaware Water Gap National Recreation Area.

Montgomery, M.E. 1999. Woolly adelgids in the southern Appalachians: Why they are harmful and prospects for control. In: Gibson, P. and C. Parker, (Eds.), Proceedings of the Appalachian biological control initiative workshop. USDA, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV, FHTET-98-14. 59 p.

Montgomery, M.E. and S.M. Lyons. 1996. Natural enemies of adelgids in North America: Their prospect for biological control of *Adelges tsugae* (Homoptera: Adelgidae). In: Salom, S.M., T.C. Tigner, and R.C. Reardon, (Eds.), Proceedings, First hemlock woolly adelgid review, 12 October, 1995, Charlottesville, VA. USDA, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV, FHTET-96-10: 89-102.

Mullins, J.W. 1993. Imidacloprid: a new nitroguanidien insecticide. In: Duke, S.O., J.J. Menn, and J.R. Plimmer (eds.), Pest control with enhanced environmental safety. American Chemical Society Symposium, ASC, Washington DC: 183-189.

Myers, W.L. and R.R. Irish. 1981. Vegetation survey of Delaware Water Gap National Recreation Area. Final Report, USDAI National Park Service.

Onken, B., D. Souto, and R. Rhea. 1999. Environmental Assessment for the release and establishment of *Pseudosymnus tsugae* (Coleoptera: Coccinellidae) as a biological control agent for the hemlock woolly adelgid. USDA, Forest Service, Morgantown, WV.

Quimby, J. 1996. Value and importance of hemlock ecosystems in the eastern United States. In: S>M> Salom, T.C. Tigner, and R.C. Reardon, eds. Proceedings of the First Hemlock Woolly Adelgid Review, Charlottsville, VA, 1995. USDA Forest Service, Forest Health Technology Enterprise Team-Morgantown, WV. FHTET 96-10. pp1-8.

Rhea, J.R. 1996. Preliminary results for the chemical control of hemlock woolly adelgid in ornamental and natural settings. In: Salom, S.M., T.C. Tigner, and R.C. Reardon, (Eds.), Proceedings, First hemlock woolly adelgid review, 12 October, 1995, Charlottesville, VA. USDA, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV, FHTET-96-10: 89-102.

Sasaji, H. and M.S. McClure. 1997. Description and distribution of Pseudoscymnus tsugae sp. Nov. (Coleoptera: Coccinellidae), an important predator of hemlock woolly adelgid in Japan. Annals of the Ent. Soc. Am., 90:563-578.

Schroeder, M.E. and R.F. Flattum. 1984. The mode of action and neurotoxic properties of the nitromethylene heterocycle insecticides. Pestic. Biochem. Physiol. 22: 148-160.

Schweitzer,D.1994. Hemlock woolly adelgid and native hemlock lepidoptera. Memorandum to state Natural Heritage Programs and stewardship staff at The Nature Conservancy offices in the ERO states, and NC, SC, GA, and Great Smokey Mountains National Park. (May 19).

Sciascia, J.C. and Ellen Pehek. 1995. Small mammal and amphibian populations and their microhabitat preferences within selected hemlock ecosystems in the Delaware Water Gap National Recreation Area. Draft final report, 39pp.

Silcox, C.A. 2002. Using imidacloprid to control hemlock woolly adelgid in the Eastern United States. In: Onken, B., R. Reardon, and J. Lashomb (eds.), Proceedings, Symposium on the hemlock woolly adelgid In Eastern North America, February 5-7, 2002, East Brunswick, NJ. N.J. Agricultural Experiment Station Rutgers. 280-287 p.

Smith, S.F. and V.A. Krischik. 1999. Effects of systemic imidacloprid on *Coleomegilla maculate* (Coleoptera: Coccinellidae). Envir. Entomol. 28(6): 1189-1195.

Snyder, C., J. Young, D. Smith, D. Lemarie, R. Ross, and R. Bennett. 1998. Influences of eastern hemlock decline on aquatic biodiversity of Delaware Water Gap National Recreation Area. Final Report to the National Park Service.

Tattar, T.A., J.A. Dotson, M.S. Ruizzo, and V.B. Bruce. 1998. Translocation of imidacloprid in three tree species when trunk and soil injected. Journal of Arboriculture 24: 54-56.

Tattar, T.A. and S.J. Tattar. 1999. Evidence of the downward movement of materials injected into trees. Journal of Arboriculture 25(6): 325-332.

USDA Animal and Plant Health Inspection Service. 2002. Draft. Use of Imidacloprid formulations for the control and eradication of wood boring pests: Assessment of the potential for human health and environmental impacts.

Van Driesche, R.G. S. Healy and R.C. Reardon. 1996. Biological Control of Arthropod Pests of the Northeastern and North Central Forest in the United States: A Review and Recommendations. USDA, Forest Service, Forest Health Technology Enterprise Team, Morgantown, WV, FHTET-96-19: 10.

Steward, V.B. and T.A. Horner. 1994. Control of hemlock woolly adelgid using soil injection of systemic insecticides. J. of Arbriculture 20(5):287-288.

Wallace, M.S. and F.P. Hain. 1998. The effects of predators of the hemlock woolly adelgid in north Carolina and Virginia. USDA, Forest Service. Hemlock Woolly Adelgid Newsletter # 3: 3.

Webb, R.E., J.R. Frank, and M. J. Raupp. 2003. Eastern hemlock recovery form hemlock woolly adelgid damage following Imidacloprid therapy. Journal of Arboriculture. 29(5): 298-302.

Yamasaki, M., R.M. DeGraaf, and J.W. Lanier. 2000. Wildlife habitat associations in eastern hemlock – birds, smaller mammals, and forest carnivores. In: Proceedings of a Symposium on Sustainable Management of Hemlock Ecosystems in Eastern North America, edited by K.A. McManus, K.S.Shields, and S.R.Souto. pp.135-141.

Young, J.A., D.R. Smith, C.D. Snyder, and D. P. Lemarie. 1998. A landscape-based sampling design to assess biodiversity losses from eastern hemlock decline.